Estimation of solid mass retention and load reduction efficiency by the Stormwater Management StormFilter® system at the Kearny Mesa Maintenance Station

Overview

This study explored two different approaches to estimating the load reduction efficiency of the Stormwater Management StormFilter® (StormFilter) system at the California Department of Transportation (Caltrans), Kearny Mesa Maintenance Station (KMMS). One approach is based on the analysis of soil and media samples collected during maintenance of the StormFilter system. The alternative approach is based on results of monitoring for total suspended solids (TSS). The load reduction efficiency ranges from 67 to 78% as determined based on soil and media samples and 36% as determined by TSS data.

Introduction

Estimates of mass removal and associated load reduction efficiencies by the StormFilter system at the Caltrans KMMS have been made based on information acquired from Stormwater Management Inc. (SMI) field sampling, resulting laboratory analyses, and TSS data from the National Stormwater BMP Database (NSBMPD). Particle size distribution and total volatile solids analyses were performed to characterize accumulated material in the system cartridge bays. Accumulated material depth and samples of the material were used to estimate the overall mass of settled material in the system. Core samples collected from spent cartridges were used to approximate the mass of the load retained by the cartridges. Results of mass removal and load reduction efficiencies were contrasted between the soil and core sample derived values and the TSS derived values.

The KMMS StormFilter system consists of three vaults in parallel/series containing a total of 79 coarse perlite/coarse zeolite cartridges operating at 57 L/min/cartridge (15 gpm/cartridge). The vaults of the StormFilter system operate in parallel but are installed in series. Flows exceeding the design capacity of the first vault pour through a bypass pipe in the inlet bay of the second vault, and so on. Each vault discharges filtered effluent separately and thus acts in parallel. In accordance with the SMI standard vault series notation, the first vault to receive influent is referred to as the upstream vault. The next vault to receive flow is the middle vault and the last vault is the downstream vault. The upstream and middle vaults contain 26 cartridges. The downstream vault contains 27 cartridges. The system treats stormwater runoff from 6100 m^2 (1.5 acres) of a road equipment maintenance facility. Eucalyptus trees, located on-site, continuously contribute leafy debris to the system.

Procedure

Site information and samples were collected at the KMMS site on October 29, 2002 by SMI. From each of the vaults, a composite soil sample of settled material was taken consisting of a grab sample from each corner of the cartridge bay and one from the center. The samples were collected in 500 mL HDPE jars. The samples are displayed in Photo 1 of the appendix.

Distributed measurements of settled material depth were recorded on the Standard Field Site Observation Form. A StormFilter cartridge from each vault was delivered to the SMI laboratory in Portland, Oregon, for the extraction of spent media samples.

Sub-samples of the three composite samples were used for total volatile solids (TVS) testing, particle size distribution analysis and density estimation. Upon receipt of the samples at the SMI lab, they were individually stirred prior to the extraction of representative sub-samples for TVS analysis by Severn Trent Laboratories in Tacoma, Washington, according to ASTM D2974. As the sample collected from the upstream vault had high moisture content, the remaining composite sample was dried after sub-sample extraction for TVS testing, prior to performing the particle size distribution analysis and density estimate. Additional sub-samples from each composite were used for internal particle size distribution analysis performed according to Gee & Bauder, (1986). Organic constituents were not removed prior to the particle size analysis. By appearance, the soil samples contained a large amount of composted and leafy material. The medicinal odor of the soil samples was evidence of the presence of eucalyptus in proximity to the StormFilter system.

The composite sample remnants and the settled material depth data were used to determine the mass of settled material. The volume of settled material in each cartridge bay was calculated by multiplying the average depths by the available settling area. Converting the volumes to a mass required determining the bulk density of samples collected from the floor of each cartridge bay. The volume of each remaining composite sample was measured prior to determining the dry weight of the samples. The resulting settled material densities were multiplied by the settled material volume of the respective vaults to obtain the mass of settled material on the floor of each cartridge bay. It was assumed that the volume of the dry mass would provide a sufficient estimate of the wet mass volume. Given that the soil samples collected from the middle and downstream vaults were dry, using the volume of the dry mass likely induced negligible error. The upstream cartridge bay soil sample contained moisture. In this case, applying the dry sample volume to the accumulated wet material volume may induce error resulting in a higher estimate of mass.

To estimate the mass of material retained by the cartridges, spent cartridges were delivered to the SMI lab for core sample extraction. The media orientation in each cartridge consists of two vertical layers: a 3-inch, outer layer of coarse perlite and a 4-inch inner layer of coarse zeolite. The media of the cartridge taken from the upstream vault was disturbed during transport due to center tube displacement, see attached Photo 2. Mixing of zeolite and perlite layers upon center tube displacement made extracting representative samples of each media type unfeasible. Based on visual observation, the upstream cartridge media appeared to retain more material than the middle cartridge media which in turn appeared to retain more than the downstream cartridge media. Photo 3 shows samples of the media from in the middle and downstream cartridges. For the middle and downstream cartridges, samples were taken using two core samplers made of 2-inch diameter PVC pipe with a beveled inner edge at the end that is driven into the media. The other end was outfitted with a handle and an adaptor for a galvanized cap thereby providing a surface to enable pounding the core sampler through the media, see Photo 4. A core sampler was driven into each layer of the cartridges. The cores were then extracted by removing the surrounding media. The lower end of the coring tube was then restricted by sliding a hand below the tube thereby preventing much sample loss during coring tube removal from the cartridges. Any sample loss was collected by brushing the remaining sample onto a piece of paper.

By utilizing core samplers, an even, vertically distributed sample of each media type can be extracted from the cartridges. This is very important considering uneven horizontal distribution of solids trapped in the media. As evidenced upon media excavation of the cartridges, much of the trapped material was located in the lower portion of the cartridges, see Photo 5. Considering that retained material in the cartridges gradually settle lower in the

cartridge, a greater amount of material collects in the lower portions of the cartridges. Dislodging and resettling of the material during transport to the SMI laboratory may have also contributed to a larger amount of material lower in the cartridges.

The bulk density, using dry weight basis, of the spent media samples was compared to that of unused media to determine the mass of material accumulated in each sample which was then extrapolated to the represent the mass retained by cartridges in each vault. Although the perlite in the coring tube appeared to compact as the tube was driven through the media, a constant sample depth equal to the height of media in the cartridge was used to calculate the undisturbed volume of representative sample within the tube. The density of unused zeolite was calculated using the dry mass and volume of unused zeolite packed in a coring tube. The density of unused perlite was determined using the dry mass and volume of unused perlite as measured in a 1000 mL Nalgene container. Attempting to pack unused perlite in a coring tube would prove unrepresentative of the sample volume extracted from the cartridges. The increased surface area of the tube would restrict the packable volume of perlite as the coarse perlite has a jagged texture and tends to pack better in a space with a less restrictive surface area. Hence, more voids would be present in the unused perlite packed in the coring tube than there was in the cored spent perlite sample. Estimates of mass retained by a media type within a given vault were determined using density differences between spent and unused media. The density difference for a given media type was then multiplied by the volume of media contained within a vault to calculate the mass of material retained.

Initially, values of mass retained were derived from both zeolite and perlite samples. However, the cored perlite samples contained some zeolite. Considering that zeolite is denser than perlite and that the spent samples were compared against unused, unmixed media samples of the same type, a portion of the mass retained by the spent perlite is actually the additional mass of zeolite in the perlite sample. Therefore, the resulting mass retention estimate for perlite is biased to the less conservative end. The converse is so for the cored zeolite samples which did contain some perlite. Therefore, in addition to estimates of mass removed based on analysis results of cored perlite and zeolite samples, a conservative value of mass removed will also be calculated based on the mass retention values calculated for the cored zeolite samples, alone, extrapolated to represent all media in the cartridges.

As the upstream cartridge was rendered unusable for sample extraction, the density values determined using core samples from the middle vault cartridge media were assumed to represent a conservative density value for upstream vault cartridges. Downstream vaults in parallel/series encounter less polluted water due to the lower frequency of larger storm events. It would be reasonable to assume that upstream cartridges contain a greater mass of material removed from system influent. Hence the reasonable assumption that applying middle vault media sample density values for the upstream vault media densities would result in a conservative estimate of mass retained by the cartridges in the upstream vault.

Publicly available monitoring data for this system was used in an alternative method of determining mass removed by the system and in turn the system's load reduction efficiency. Influent and effluent total suspend solids (TSS) event mean concentrations (EMC) and corresponding storm flow volumes were taken from the National Stormwater BMP Database (NSBMPD, www.bmpdatabase.org). The sum of differences between load in and out is the total mass removed for the monitored storm events. The load reduction efficiency is calculated by dividing the total load out by the total load in and subtracting this value from 1.

The major assumptions involve the use of a dry sample volume to determine the dry mass content of a specific wet volume of material, extrapolation of zeolite mass retention to all media within the cartridges, and exclusion of the material collected in the inlet and outlet bays from mass retention calculations. The density of dry mass in a dry sample volume is likely higher than the density of dry mass in a wet sample volume due to shrinkage of the wet sample volume to a dry volume. Therefore the application of the dry volume density to the volume of

settled wet mass in the upstream cartridge bay will result in an overestimate of accumulated mass. This overestimate is likely compensated for by the remaining assumptions. The primary use of perlite is to remove TSS. Hence, extrapolating the mass retained by zeolite to calculate the mass retained by all the media will result in a conservative estimate of mass retention by the media since it is likely that more mass was retained by the perlite. By omitting the mass collected in the vaults' inlet and outlet bays, an added measure of conservancy is added to the final estimate of the conservative mass retained by the StormFilter system.

Results

The results of analysis performed to characterize the settled material collected from the cartridge bays are shown in Table 1. The TVS values range from 25 to 32 mg/kg with no apparent trend in the TVS values relative to the location of the vaults in series. A display of the

Table 1. Characterization of settled material from cartridge bays at the KMMS site. A coarser texture description was chosen for Caltrans DS for which the particle size distribution is located on the border of US Department of Agriculture textural definitions.

Sample ID	Total Volatile Solids (mg/kg)	Soil Texture	Particle Size Distribution
Caltrans US	29.26	Sandy Loam	55% sand, 40% silt, 5% clay
Caltrans Mid	25.11	Sandy Loam	55% sand, 40% silt, 5% clay
Caltrans DS	31.57	Sandy Loam	45% sand, 50% silt, 5% clay
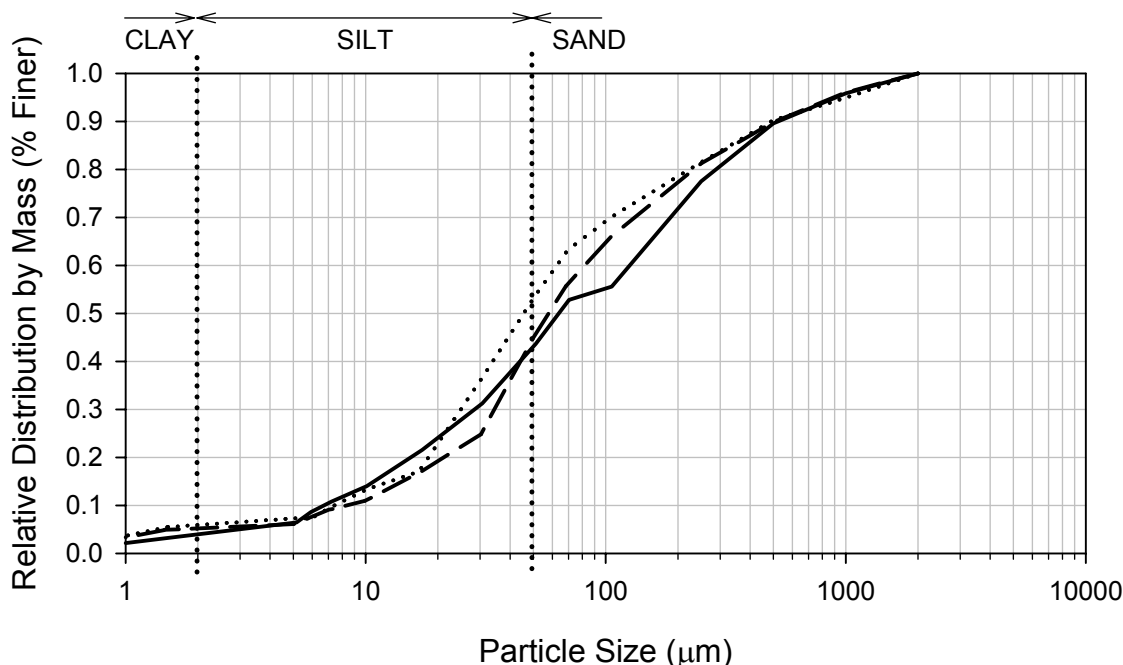
Figure 1. Particle size distributions of settled material from cartridge bays at the KMMS site. The solid line represents the distribution for the material collected the cartridge bay of the upstream vault cartridge bay, the dashed line is the material from the middle vault, and the dotted line is material from the downstream vault. The textural specifications as defined by the US Department of Agriculture are: sand between 50 and 2000 microns, silt between 2 and 50 microns, and clay less than 2 microns.

particle size distribution curves are shown in Figure 1. A sandy loam texture was found for the settled material in all three cartridge bays with the downstream soil possessing a slightly finer texture.

Estimates of mass retention by cartridges are shown in Table 2. The mass of settled material decreases from upstream to downstream vault. The values of upstream and middle vault cartridge retention, columns B and C, are equal due to the afore mentioned conservative assumption of accepting middle cartridge sample values for upstream values. Column B exhibits decreasing cartridge retention from the middle vault to the downstream vault. The opposite is shown in column C for the conservative values of cartridge retention. Based on the summation of settled material and cartridge retention, decreasing mass values from upstream to downstream vaults are evident for both approaches to estimating mass retained by the cartridge bays shown in columns D and E.

Table 2. Estimations of mass removed by the Stormwater Management Inc. StormFilter system located at Caltrans KMMS. Column A shows the mass of material settled on the cartridge bay floors. Column B lists the mass of material retained by cartridges based on the examination of both perlite and zeolite core samples. Column C contains conservative estimates of material retained by the cartridges based on the examination of the mass retained by the zeolite core sample alone. Column D shows the total mass retained by the vaults as the sum of perlite and zeolite based estimates of cartridge retained solids. Column E contains the conservative estimates of total mass retained by the vaults as zeolite based estimates of cartridge retained solids.

Vault	Settled Material (kg)	Solids Retained by Cartridges (kg)	Conservative Est. of Solids Retained by Cartridges (kg)	Total Mass Retained by Cartridge Bays (kg)	Conservative Est. of Total Mass Retained by Cartridge Bays (kg)
	A	B	C	D = A + B	E = A + C
Upstream	500	300	66	800	570
Middle	220	300	66	520	290
Downstream	30	160	130	190	160
Total	750	760	260	1500	1000

Discussion

The results of TVS analysis, ranging from 25 to 32 mg/kg, are lower than what was expected of the soil samples that appeared to contain a high amount of organic matter including compost and leaf debris, as is especially evident in the downstream vault sample shown in Photo 1 of the appendix. As the TVS values seem to not reflect the organic content of the material collected from the cartridge bay floors, an alternative method to determine the organic carbon content will be applied. Additional sub-samples of the remnant samples were recently sent to North Creek Analytical laboratory, in Bothell, Washington, for analysis of total organic carbon (TOC) according to a modification of Method 9060. Following the completion of TOC analysis the results will be presented as a supplement to this report. The TVS method determines organic carbon based on the mass of organic portion lost upon sample ignition whereas the TOC method utilizes hydrochloric acid during the volatilization of inorganic carbon followed by the combustion of organic carbon.

According to the particle size distribution results, the soil texture for the three samples was determined to be sandy loam. The particle size distribution corresponding to the downstream sample fell on the boundary of three soil textural classes: sandy loam, loam, and

silt loam. Therefore, a larger percentage of coarse particles characterize the soil collected from the upstream and middle vaults. This could be the result of a larger portion of coarser particles dropping out of suspension earlier during treatment.

The first of two estimates of mass removed by the system cartridges yielded a total of 760 kg of removed mass according to data acquired from zeolite and perlite cores. The results of utilizing data from both media types reveal decreasing mass retention by the cartridges from middle to downstream vaults. In support of this pattern of downstream decreasing mass retention, Photo 3 of the appendix shows that the media taken from the middle vault is slightly darker than the media from the downstream vault. This pattern of decrease is expected since the upstream vaults treat more storm flow. The values of solids retained by the cartridges utilizing data from both media types are a better representation of the portion of mass removed among cartridges relative to their location in the vault series. However, as previously stated, the spent perlite core samples contained some zeolite causing mass retention values to be skewed toward higher values.

The second estimate of mass removed by the system cartridges, utilizing data from the zeolite cores alone, yields a conservative mass of 260 kg. Using the zeolite cores alone provide a conservative value because the physical properties of the perlite media make it better for the removal total suspended solids and would therefore retain more mass than the zeolite. Any perlite contained in the spent zeolite samples would skew the results of the mass retained by the zeolite to a lower value. Although the less conservative values do not possess the pattern of decreasing mass retention from the middle to downstream vaults, the values acquired from extrapolating the data from the zeolite alone eliminate potential overestimation associated with the perlite mass retention estimates as described in the procedure section.

A considerable amount of the total mass removed by the system settled on the floor of the vaults. The estimated total amount of settled material in the cartridge bays is 750 kg comprising 49% of the total mass retained in the cartridge bays including the mass retained by zeolite and perlite and 74% of the conservative estimate of the total mass retained by the cartridge bays including the mass retained by the media based on analysis of zeolite cores alone. The remainder of the discussion refers to the conservative total mass estimate as the mass of material retained by the system. The mass of settled material decreases from upstream to downstream vaults as a product of the decreasing settled material depth.

The sum of the conservative mass retained by the cartridges based on the zeolite cores, 260 kg, and the mass of settled material, 750 kg, yields a value of 1000 kg for the total mass removed by the StormFilter system. This is a reasonable value considering that zeolite is not the primary TSS filtration media used in the system; any perlite in the spent zeolite sample will skew the mass estimation to a lower value; and this estimate does not consider any material collected in the inlet and outlet bays of the vaults. Excluding perlite core analysis and additional settling in inlet and outlet bays will most likely compensate for the overestimation of mass settled in the upstream vault cartridge bay, as discussed in the procedure section. A quantitative examination can be made of the degree to which the overestimation of settling in the upstream vault cartridge bay can be compensated by underestimating the mass of material collected in the media. The difference between the conservative solids retained by the cartridges using only zeolite cores, column C of Table 2, and solids retained by the cartridges using both zeolite and perlite cores, column B of Table 2, is 500 kg. This difference, due to underestimated values of material retained by the cartridges, is approximately equal to the overestimated value of 500 kg for the mass settled in the upstream vault cartridge bay and therefore serves to, if not balance, but probably over compensate for the overestimate of mass settled in the upstream vault.

The total mass removed was also calculated based on TSS data retrieved from the NSBMPD. By comparing influent and effluent TSS EMC with associated storm volumes, the aggregate load in and out for 16 storm events from March 1999 through April 2001 are 440 and

280 kg, respectively. The difference between the two values, 160 kg, is the mass removed. The TSS removal efficiency based on aggregate load removal is 36%. As stated in the procedure section, this value is calculated by dividing the total load out by the total load in and subtracting this value from 1.

Although the mass of the load removed according to the two methods, 1000 kg based on soil and media analysis and 160 kg based on TSS EMC, will be compared, there is greater significance in load reduction efficiency values. Calculations were performed to estimate an efficiency range for the soil and media analysis based load reduction. Estimating the upper and lower bounds involved the same calculation performed with the TSS EMC based load removal. By applying the TSS based load out value for use in the calculations of soil and media analysis based load reduction efficiency, an assumption is being made that the load out value is more accurate than the TSS based load in and mass removed values.

The upper bound of the soil and media analysis based load reduction efficiency is calculated by adding the TSS based load out, 280 kg, to the soil and media analysis based conservative value of total mass removed, 1000 kg, for a revised value of load in, 1300 kg. The resulting TSS removal efficiency is 78%. As there were precipitation events not represented in the load out value, the true load out value may be greater than 280 kg, thereby reducing the TSS removal efficiency.

To determine a lower bound of soil and media based load reduction, the difference in flow volume represented by the two methods of calculating load reduction efficiency will be addressed. The value of soil and media based mass removal can be proportionally adjusted to correspond with the amount of rainfall generating the monitored storm events. The soil and media samples correspond to the treatment of storm flow resulting from precipitation events occurring from the time of installation to that of maintenance. The TSS EMCs correspond to specific storm flow events generated from a portion of the total rainfall that contributed to the value of mass retained based on soil and media analysis. The portion of total load removed by the system, from the time of installation to maintenance, that contributed to the TSS based mass removal value is equal to the portion of total precipitation that contributed to the monitored storm events. Based on precipitation recorded at the San Diego Airport, operated by the Weather Service Office, a total of 51 cm (20 in) fell during the StormFilter system operation prior to maintenance. According to the NSBMPD, the corresponding rainfall for the monitored storm events is 29 cm (11 in). Therefore, the estimated aggregated total mass removed, based on the TSS information and corresponding to the monitored storm events, comprises approximately 57% of potential flow to the system.

Assuming the conservative mass removed, as calculated using results of soil and media analysis, represents 100% of the mass collected as a result of the 51 cm of precipitation, 57% of 1000 kg, the conservative estimate of mass removed, is 570 kg. The lower bound of TSS removal efficiency would therefore be 67% as calculated using the same method as described above to determine the corresponding efficiency based on a different value of mass removed, 570 kg, added to the load out, 280 kg, for a new value of load in, 850 kg. The true value is likely to be higher than 67% because the assumption of a linear relationship between precipitation and sediment delivery to the system does not account for the carrying capacity differences of storm flow resulting from varying rainfall intensities. For example, high rainfall amounts of low intensity will result in the delivery of a large volume of influent to the system at low flow rates. In this example, it is likely that flow carries proportionately less material into and out of the system contrasted with the mass estimation for the same flow volume based on a linear representation between mass and rainfall amount. Therefore, the monitored storm events, representing 57% of the potential flow to the system, is likely to have delivered more than 57% of the total mass. If the mass retained during the monitored storms is higher than 570 kg the TSS removal efficiency would increase.

A discrepancy exists between the values of mass removed between the methods using NSBMPD data and the results of soil and media analysis. Scaling the mass removed, based on the NSBMPD data, to correspond to 100% of the potential storm flow to the system increases the value from 160 to 280 kg. It is a third of the mass removed determined by results of soil and media analysis and is also just half of the mass settled in the upstream cartridge bay.

The smaller value represented by the NSBMPD may be a result of material bypassing the sampler intake at the influent end. A Caltrans KMMS case study, conducted by SMI (2002), put forward the concept that automated sampling inability to collect leafy matter will artificially depress influent concentrations and negatively affect removal performance. The study focuses on nitrogen removal by the StormFilter system. Leafy matter will bypass the influent sample intake of an automated sampler because the tube diameter of the sample intake is too small. The leafy matter then collects in the system and degrades into a form capable of leaving the system and being collected by the effluent sampler. Unlike a BMP such as a swale, in which leaves may be carried over and out with the flow, StormFilter systems are efficient at retaining whole, leafy material as evidenced by Caltrans (1999). As nitrogen and TSS share a common source in leafy matter, the conclusions of SMI (2002) are applicable to the aggregate load reduction efficiency. For this reason, acquiring an efficiency range as determined by analyzing soil and media samples provides valuable insight to the mass removed by the StormFilter system.

The resulting differences from the two approaches present a quandary in sampling, analysis and contaminant definitions. For the case of TSS, if larger leafy material was collected in an influent sample, it would likely be larger than the size specification for a suspended solid and be excluded from TSS analysis. Even if this were not the case, influent samples may not correspond with effluent samples of the same storm, considering that material may not exit the treatment system during the same storm it entered the due to its detention time in the system.

Conclusion

Upon applying different approaches to estimating the solid mass retention and load reduction of the Caltrans KMMS StormFilter system, is suggested that the method utilizing analysis results of soil and media samples provides a different perspective of load reduction efficiency in contrast to the method utilizing TSS EMC results of monitoring with automated samplers. A conservative estimate of the mass removed by the system is 1000 kg based on analysis of soil and media samples collected during system maintenance. The corresponding load reduction efficiency ranges from 67 to 78%. The mass removed by the system is 283 kg based on NSBMPD data of TSS EMC for monitored storm events. The corresponding load reduction efficiency is 36%.

The discrepancy between efficiencies is primarily due to the inability of automated samplers to collect influent samples representative of corresponding effluent samples due to the limited size of the sampler intake opening, definitions of TSS, and the irregular detention time of leafy material within the StormFilter system. This becomes problematic in any type of BMP for which pollutants being retained and transformed in the system are not picked up in influent samples but are being picked up in effluent samples. Thus removal efficiencies appear reduced compared to actual efficiencies.

References

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Appendix

Photo 1. Samples of material accumulated on the cartridge bay floors of the StormFilter system at Caltrans KMMS. Shown from left to right, the samples were taken from the upstream, middle, and downstream vaults.

Photo 2. Displaced center tube in the cartridge taken from the upstream vault. Sample extraction was attempted, although it became evident that collecting representative vertically distributed samples of each media type would not be feasible.

Photo 3. A side by side comparison of spent zeolite and perlite media from cartridges retrieved from midstream and downstream vaults at Caltrans KMMS.

Photo 4. Two core samplers used to isolate samples of two vertically oriented media types during cartridge excavation.

Photo 5. Material retained by the inner zeolite and outer perlite media layers of a cartridge retrieved from the middle vault at Caltrans KMMS.